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SOME EXPERIMENTS ON LIQUID HELIUM HEAT TRANSFER — CHARACTERISTICS AFFECTING STABILITY OF SUPERCONDUCTING MAGNET OPERATION *

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Heat transfer from 25 μm thick, 6.36 mm wide Nb tape into boiling helium in vertical channels of 1.7 x 21 mm cross section was studied. Normal zones were initiated by heaters attached to the tape surface not in contact with the liquid. Two heat transfer effects of possible importance for superconductor stability were observed: 1. Steady normal zones enabling the measurement of localized heat transfer, and 2. Heat transport to neighboring tapes by means of the coolant. 1. Steady normal zones are those that neither grow nor decay; they occur at current densities of 13 to 17 kA/cm², corresponding to heat transfers of 0.45 to 0.8 W/cm² for the normal portion of the tape. Fluctuations of the length of the normal zone are < 0.4 mm. Comparison of measured temperature profiles with calculations yields localized heat transfer values. A heat transfer ~3 times higher than the peak nucleate boiling value of 0.42 W/cm² (measured for brass tapes) exists in a 2 mm wide region near the normal to superconducting boundary. It is inferred that this is the region where the gaseous film covering the normal zone terminates and wetting by the boiling liquid begins. 2. In a current range where the normal zones decay again, it is observed that heater pulses (square, 1 s long) larger than a critical level (0.7 W) cause normal zones to appear in tapes directly above the heater-induced normal zone, with a delay of the order of 0.1 s. Suggested explanation: The heat from pulse and induced resistive zone vaporizes the limited amount of liquid helium in contact with the zone and, before convection has time to develop, the helium becomes superheated above the critical 6 - 8 K. As it then rises normal zones are created.

I Introduction

Information on heat transfer is important when judging the stability of superconducting coils. The available data applies mostly to what is called steady state heat transfer. There are two obvious shortcomings: a large scatter of published data (pointing to the importance of hidden parameters) and a lack of data in the intermediate region between nucleate boiling and film boiling. Less obvious shortcomings: when applying such data to the stability problem one needs information on a highly time dependent heat transfer - indeed, in the steady state a healthy superconducting winding needs no heat transfer at all - , moreover, any disturbance, any initiation of an instability, is likely to be a function of position, whereas most steady state heat transfer values are averaged over surfaces of the order of cm².

The original purpose of the investigation, in collaboration with S. G. Sydoriak, was to measure steady state heat transfer to helium in channels and its dependence on various parameters, especially its dependence on liquid helium flow speed as expected from a correlation of existing experimental data,[1] and possibly useful for the control of quenches.[2] After steady normal zones in a superconducting Nb tape over a considerable range of current were observed, the author decided to make further investigations, as systematically as possible, with the existing apparatus.

When a superconductor is disturbed by means of a local heat pulse, the ensuing normal zone either grows or decays, depending on the balance between Joule heating by the transport current and cooling by coolant action and conduction. If there is a steady normal zone, it is expected to be in a state of unstable equilibrium, occurring at specific, well defined values of current and temperature, and is referred to as minimum propagating zone (MPZ).[3,4] In contrast, the observed steady normal zones (SNZ) do not decay or grow, moreover, they exist over a wide range of currents. The minimum propagating zone has the same kind of equilibrium as that of a ball placed on top of a pointed stick - it is expected to fall off. However, the ball's not falling off points to the action of possibly quite complicated mechanisms, such as a juggler at the other end of the stick. SNZ are unlike MPZ; they are in the same class as the juggled ball. At present no plausible explanation for the balancing mechanism is known. SNZ have been observed on occasion [5,6] and could sometimes plausibly be explained by hot spots left in insufficiently cooled places, such as under spacers. The SNZ reported here have no such explanation. Their behavior is described in some detail. They can be put to use in measuring localized heat transfer, especially in the otherwise hardly accessible region between nucleate and film boiling.

A second effect, observed and described, is the occurrence of normal zones in tapes adjacent to the pulsed heater but thermally insulated from it. The anomalous heat transport is a transient process on a time scale of the order of tenths of seconds.

Both processes can be of importance for the stability of bath-cooled superconducting magnets.

II Experimental setup

The experimental results are obtained from an annular flow chamber consisting of two concentric fiber glass-epoxy cylinders, approximately 22 cm in diameter, held 1.7 mm apart by teflon dividers that form 30 vertical channels, each 22 mm wide, extending down the 30 cm long annular space. Thin brass tapes, 3 mil thick, 6.36 mm wide are wound as 3 single turns and as a spiral of 4 turns around the inner cylinder and are in one-sided contact with the coolant in the channel. A niobium tape of the same width but only 1 mil thick forms a spiral of just over 3 turns (91.5 channels) between the middle and top single brass turns. A centrifugal pump connected to

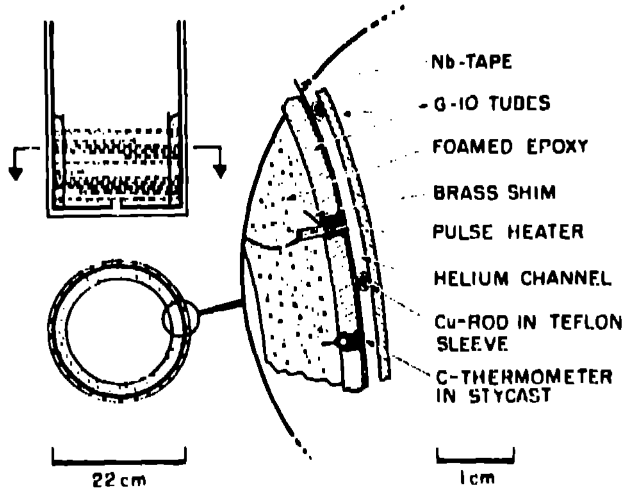

FIG. 1 CROSS SECTION OF APPARATUS AND DETAIL

*Work performed under the auspices of the US Dept. of Energy.

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the center of the lower plenum allows the liquid helium to be driven upwards through all channels in parallel at speeds up to 15 cm/s. 34 current and potential leads, 18 thermometers and 3 pulsed heaters (these are in the middle and at one third and two thirds of the Nb tape) are used to operate and monitor different sections of the tapes. Details of the apparatus are illustrated in Fig.1.

The carbon thermometers are individually calibrated between 1.5 and 30 K. They are encased in stycast and attached with stycast through slots in the inner cylinder to the back of the tapes so that the separation between the copper leads and the tape is minimal. Through similar slots the heaters - wire wound on copper forms - are soldered to thin brass foils spotwelded to the Nb tape. The brass foils serve also as potential probes. A foamed epoxy backing reduces heat leaks through the leads.

Heat transfer was measured in the brass tapes and critical heat flux for transition from nucleate to film boiling was measured in 6 different channels and two different tapes to be between 0.38 and 0.45 W/cm² with the average at 0.41. The recovery heat flux was between 0.276 and 0.343, with the average at 0.31 W/cm². It was found that many thermometers were reading low (possibly being caused by cracks admitting liquid helium to the thermometers or by poor contact to the brass tapes). The heat transfer versus the temperature difference from the highest reading thermometers is given in Fig. 2. The nucleate boiling region differs from data established in the literature.

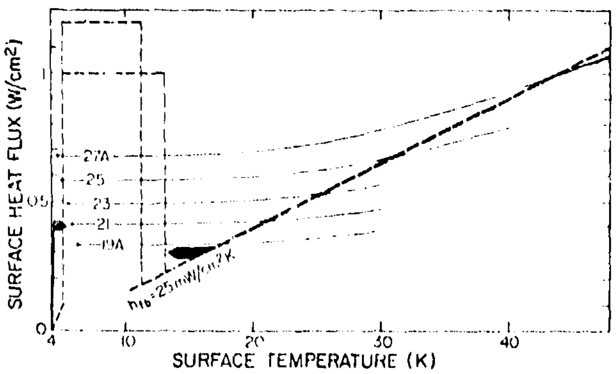

FIG.2 $\dot{q}$ versus T from brass tapes. Black arrows give critical nucleate boiling flux and critical recovery flux for brass tapes. Dots at lower end of $\dot{q}(I)$ curves are $T_c(I)$ under the assumption of I_c=32 A. Dashed curves: heat transfer that matches measured SNZ temperature profiles.

The resistivity versus temperature of the Nb tape was measured during slow cooldown as given in Fig. 3. From this the power production in the resistive Nb tape is obtained (s. Fig. 2). Equating the power production with the heat transfer gives the temperature of the resistive Nb tape. The critical current of the Nb tape at 4 K is in excess of 30 A (limit of current leads).

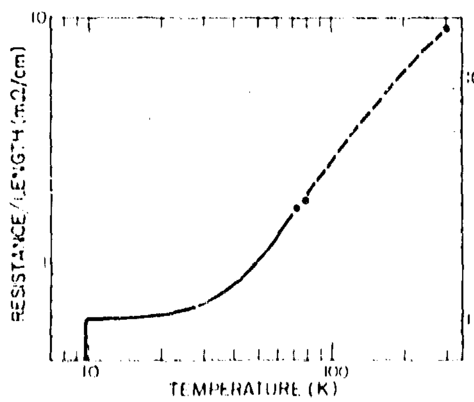

FIG.3 Resistance of Nb tape versus temperature. Solid curve from C-thermometers during slow cooldown; dashed curve connects RT and liquid N² points.

III Steady normal zones

The Nb tape, carrying a current less than the critical current, can be made resistive by means of heater pulses.

The first surprise is that for a current ≤ 21.5 A the normal zone (NZ) created by the heater pulse will decay by itself. This was observed up to the highest heater pulses of 27 W and 2 s (54 J). At currents ≥ 22 A the NZ does not decay, provided the heater pulse exceeds a very small threshold value. The threshold is 0.4 J at 22 A; 0.23 J at 24 A and < 0.1 J at 26 A. At 21.5 A the power produced in the normal Nb tape per cooled surface is 0.43 W/cm².

The second surprise is that the non-decaying NZ does not grow by itself and is in fact quite steady. At constant current the voltage across a SNZ, interpreted as length of resistive zone shows fluctuations of less than ±0.4 mm. The length of a SNZ, after it is established by a heater pulse, usually extends from one to several channels and is only little affected by changes in current. After increasing the current to ≈ 24 A the SNZ can grow by several channels and come to a stop again; at yet higher currents, usually > 25 A it grows without stopping, or until the current is slightly lowered again. The growth occurs at a rate of one to several cm/s.

The extent and location of the SNZ depends on the history of the current changes. By monitoring the different potential taps it was observed that the larger SNZ existed rarely in one continuous resistive section; instead there were usually two or three resistive zones in adjacent turns. The resistive zones in adjacent turns were either created right from the beginning by a sufficiently large heater pulse, or they suddenly appeared during a growth process. The largest SNZ observed consisted of one or two fully resistive turns with superconducting portions left in the bottom turn. Fig. 4 is an illustration of SNZ growth and decay. The dashed trace is a small SNZ, created at 22 A (a), growing to a length of 2.4 channels at 24.8 A (b) and decaying on reducing the current to 20 A (c). Being created a second time (d) the SNZ behaves identically, however, instead of letting it decay the current is increased again at 21.6 A., just above the first decay step (e). At 27 A the SNZ grows (f) to > 50 channels (off scale), the growth is checked by reducing the current. The SNZ decays to 22 ch at 20 A (g) and further to 1 ch at 18 A where the current is reversed again. Finally at 27.5 it grows again, leading to a quench (i). The solid trace in Fig. 4 shows a much longer history with very large SNZ. Remarkable is the situation after the growth to 77 ch length at (39), repeated at (41); the growth to 84 ch took several seconds and occurred automatically, the power supply being at its maximum voltage limit. The fact that total recovery (42) could take place, after 90% of the winding was resistive and dissipated 84 W for several seconds, demonstrates the strength of the SNZ effect.

Some general features emerge clearly: growth can occur at currents > 22 A, decay at currents < 21.5 A. Between growth and decay events the SNZ is essentially constant: the SNZ follows a line of almost constant length of resistive zone. For large SNZ this is sometimes obscured by the fact that growth or decay is still going on while the current is being changed on a similar time scale; slower changes, in Fig. 4 between (25) and (28), at (33) and (34)(36) show the constancy of the SNZ. The whole solid trace took 300 s to make.

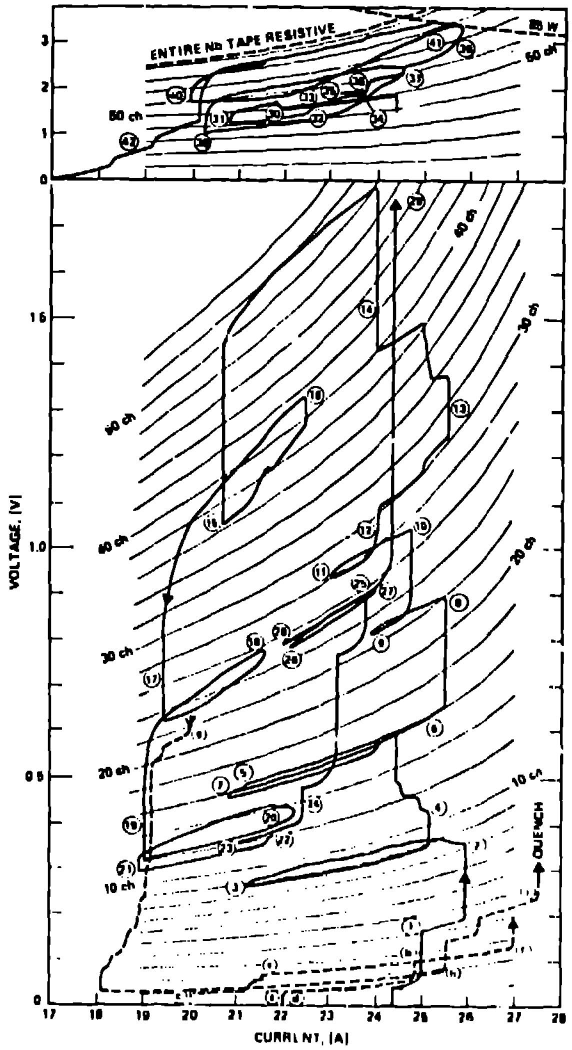

FIG.4 History of SNZ when transport current is varied. Initiation of SNZ (at a,d and 24.3A) is by heater pulse. Dashed trace: short SNZ (such as used to measure temperature profile); solid trace: largest SNZ observed.

A large number of such SNZ histories were traced. The highest growth currents of 27.7 A were generally observed at a high helium level (up to 60 cm above the rim of the channels), but quenches were more frequent, even at lower currents. At low helium level, generally several cm below the upper rim, cycling of the SNZ was easier, allowing the occurrence of the largest SNZ observed. Also, it seems that during cycling the SNZ moves into the most favorable places.

While convective movements in the coolant within a channel probably play a role in the SNZ mechanism, the actual flow through a channel seems to be less important. This is shown by the small but measurable effect of forced circulation by pumping or by heating the brass tapes above or below the Nb tape; the net change in the SNZ length is < 2 mm, either larger or smaller, depending on position of SNZ, but the fluctuations are noticeably larger, though still < 1 mm

From Fig. 2 it is seen that for currents above 27 A the heat production is always greater than the possible heat transfer by film boiling into the liquid, consequently a limitless increase in temperature will lead to a growth of the SNZ and to a quench, as is indeed observed. It could be that film boiling in channels is affected by other parameters and that growth at lower currents occurs for similar reasons.

Calculations indicate that below 21 A only those portions of tape covered by channel dividers remain resistive; at 18 A cooling is sufficient to cause complete collapse of the remaining resistive zones. Observation showed that in some cases the current had to be reduced to 17 A before the last vestige of SNZ disappeared; on raising the current a SNZ had to be started again by a heater pulse. The large spread of decay current reflects the fact that the covered area by channel dividers can vary from almost nothing to about 2 mm in some places.*

IV Localized heat transfer

The SNZ consists of a resistive region (assumed to be fully normal and having sharp edges), transferring heat by film boiling, and by adjacent superconducting regions, where heat transfer, as far as it is necessary, is by nucleate boiling. Since the boundary between normal and superconducting regions is stationary it is possible to calculate the local heat transfer from a measured temperature profile. The apparatus used is not ideally equipped for such a measurement, however, some favorable circumstances allow a process leading to a good estimate of the localized heat transfer.

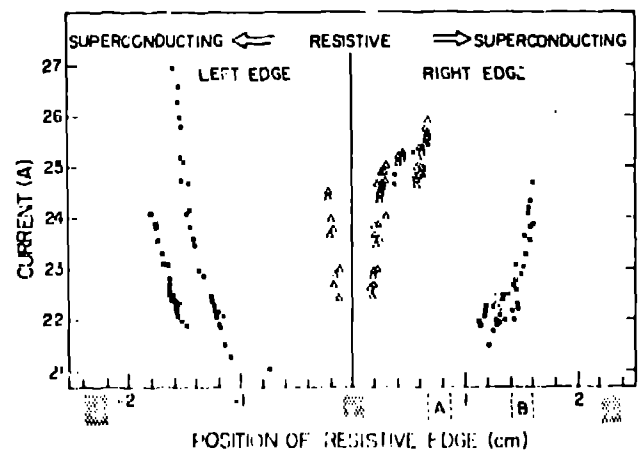

FIG.5 Position of the two resistive edges of a short SNZ as function of transport current.
Absolute accuracy of position is ± 0.8 mm due to the uncertainty of exact position of potential tap; relative accuracy is much higher.
Position of thermometers: A in ch 11; B in ch 25 and ch 25
Left and right edge are in ch2' and 26 (upper turn) for ●, ch9 and 11 for △, ch24 and 25 (lower turn) for □.
The jump in trace △ at 24.8A and in trace ● at 22.2A seems to coincide with the position of the thermometers.
Premature termination of one edge (left edge △ at 24.6A, right edge ● at 24.8A) indicate growth events.

Measurements of the length of short SNZ indicate a distinct dependence on the transport current as given in Fig.5. It is possible to position the SNZ boundary near a single thermometer and move it across in small steps by changing the current. Fig. 6 shows temperature profiles thus measured. Instead of moving a thermometer across a fixed SNZ boundary one moves a SNZ boundary across the position of the thermometer. The temperature profile probably changes somewhat with increasing current, yet indications are, that such changes are negligibly small in the range of currents under consideration; thus the measured temperature profile approximates very closely the profile of a SNZ boundary at fixed current. The measured temperature profiles do not reach much beyond 8

*Not necessarily the correct explanation for the spread in decay current, but the variation in channel width of 1.7±0.1mm translates into channel dividers (teflon sleeves more or less squeezed) covering more or less tape. On the other hand there is 1 mil thick and 3/32" wide mylar adhesive tape between the channel divider and the tapes, stuck across the tapes. Similar adhesive tape is between the metal tapes to give a smooth surface.

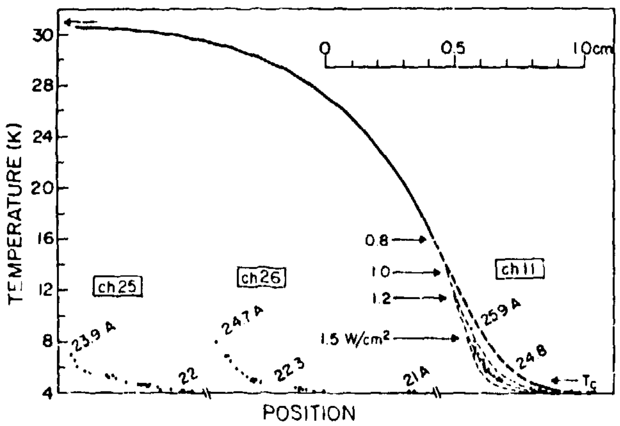

FIG.6 Temperature profiles of the right edge of SNZ, from FIG.5. Points: measured; Curves: calculated.

K; although temperatures up to 17 K were measured, their position was uncertain, because in all three cases the SNZ grew to a larger size between the potential taps.** The measured temperature fluctuations are about ± 0.1 K at 5K and ± 0.15K at 7K and have periods of the order of 0.5 s; they seem to be somewhat smaller than the resistive fluctuations equivalent to ± 0.14 mm of boundary movement.

The solid line in Fig. 6 is a calculated temperature profile according to the one-dimensional solution to the steady state heat equation

$$T = C\, e^{\sqrt{h/kd}\; x} + \dot{q} + T_0$$

k(= 0.4 W/cm K) is the thermal conductivity of Nb; for $T > T_c(I)$, $\dot{q}$ is assumed to be $\dot{q}(I)$ from Fig. 2 , or $j^2\rho/d$,(d thickness of tape), for $T < T_c$, $\dot{q} = 0$; for $\Delta T > 12$K, h is taken from Fig 2 as $h_{fb} = 25$ mW/cm²K; for $\Delta T < 1$K $h_{nb} = 0.1$ W/cm²K gives the best fit. C is an integration constant, with dimension of temperature, that simply shifts the origin of x.

For 1K < ΔT < 12K, covering a region about 2 mm long, a constant heat transfer is assumed, and the solution to the heat equation becomes

$$T = \frac{1}{2k}\left(\frac{\dot{Q}}{d} - j^2\rho\right)x^2 + C_1 x + C_0$$

The resulting temperature distribution is a parabola; the two integration constants only cause horizontal or vertical shift. In Fig. 5 solutions for four different choices of $\dot{Q}$ between 0.8 and 1.5 W/cm² are joined (at the horizontal arrow) to the film boiling solution and continue below T_c with the nucleate boiling solution. The measured points fall between the curves for 1 and for 1.2 W/cm². The other two distributions fit similar values, except that the nucleate boiling tail in ch 25 requires an even lower h_{nb}.*

It is fairly plausible to interpret this high heat transfer as being caused by the re-wetting region between liquid and gas film. The value of 1.2 W/cm² would indicate a rate of evaporation of 0.094cm³/s per cm length of a 2 mm wide boundary. It could be that a high temperature gradient is essential in order to straddle the temperature range of 2K < ΔT < 10K in a distance comparable to the possible extent of the re-wetting zone. This is reason to suspect that low thermal conduction is important for the SNZ mechanism.

**There are only 5 potential taps: one either end and one at the position of each heater. Position of SNZ edge is known to the extent of being certain that there is only one boundary between taps. This is often not the case after the first growth episode of the SNZ.

*The never satisfactorily explained problem with the thermometers on the brass tapes (partly responsible for making the apparatus unfit to pursue the purpose for which it was originally designed) may also afflict the thermometers attached to the Nb tapes although there is neither suspicion of this nor proof of the contrary. However, if , as a worst assumption, the thermometer should read low by a factor of 2 the match between calculation and measured points would alter only little: the 3 highest points would fit very poorly, the curved part of the profile would still fit a $\dot{Q}$ = 1.2 W/cm² parabola and the nucleate boiling part would need an even lower h_{nb}.

On entering $\dot{Q}$ = 1 and 1.2 W/cm² in Fig. 2 it is found, as required, that the Maddock-James-Norris criterion[7] is fulfilled. The areas above and below the $\dot{q}$(25A) line enclosed by the dashed heat transfer curves are equal to within a few percent.

V Anomalous heat transport

It was observed that for any but the smallest heater pulses a NZ appeared not only near junction of heater and tape (original NZ) but also in the adjacent tapes in locations directly above the heater (neighboring NZ). Heat transport through the channel dividers is calculated to be of the order of mW per degree temperature difference between the tapes (notwithstanding the Cu rod inside the teflon sleeve), thus even a temperature difference of 50K would not suffice to create a NZ by conduction. Heat flow through the G-10 tube backing is much smaller.

A test series at 20 and 18 A with 1 s square pulses revealed the threshold for which a neighboring NZ was created, the extent of the neighboring zones and the delay time between onset of original and neighboring NZ as shown in Fig. 7, for 20 A. The 18 A results are only different in having original NZ approx. 20% smaller.

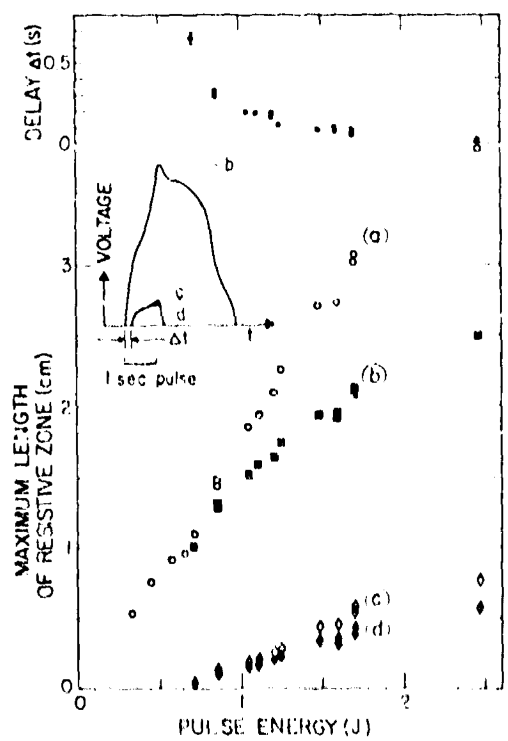

FIG. 7 Response of Nb tape to square heater pulses.
(a) total voltage, interpreted as length of resistive zone
(b) original NZ
(c) neighboring NZ in nearest tape above heater
(d) neighboring NZ in second tape above heater.
Insert: trace for 1.1 J pulse

It was also observed that at 20 and 24 A pulses in the top heater of 4.5 W and 1.5 s created a neighboring NZ above but none below the heater.

The following hypothesis may explain such behavior. The heater pulse evaporates the liquid in the immediate neighborhood of the tape, requiring 2.55 J/cm³ of liquid. Prior to the arrival of the heat pulse the liquid column in the channel is practically stagnant. The gas bubble(s) will rise and initiate convective motion in the liquid column. This process requires some time. Before the convective motion is sufficient to circulate enough fresh liquid to the hot tape the neighborhood of the pulse heater boils dry and the initial gas bubble absorbs more heat by raising its temperature. The rising hot bubble creates neighboring NZ.

Quantitative examples further illustrate the hypothesis. To evaporate the liquid in immediate contact with the tape, a volume of (width of tape)² x thickness of channel ≈ 0.07 cm³ liquid needs 0.18 J. At 0.7 W this requires 0.25 s and creates 0.5 cm³ of gas at 4K and 1 atm. Suppose no fresh liquid is available and the hot zone continues to heat the expanding bubble at the rate of 15 K/J expanding its volume by 4 cm³/J. In Fig. 8 the enthalpy per unit volume of helium at 1 atm is given. For a heater pulse of 1.1 W the liquid would be evaporated after 0.16 s and the temperature of 6 K would be reached after further 0.08 s with a bubble size of 0.9 cm³.

It is seen that these figures in conjunction with the experimental results plausibly support the hypothesis. The existing experimental data are insufficient to prove this mechanism and many questions await further study. For instance, if a convective circulation is set up, by heating the brass tapes or by pumping, would the threshold to create neighboring NZ increase, as expected, and by how much ? If longer pulses are used, how long will it take before the neighboring NZ disappear again, indicating that convective equilibrium is established ?

The data in Fig. 8 indicates that in response to a given energy the volume of the resulting bubble is roughly the same whether a little liquid helium is evaporated and superheated to a high temperature or whether a lot of liquid helium is available and the bubble is near the temperature of the boiling liquid.

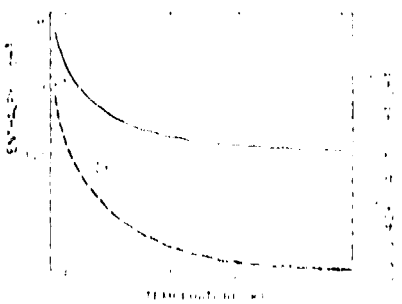

FIG. 8 Enthalpy of gaseous helium per unit volume at 1 atm. Volume of liquid at 4.2 K evaporated to form 1 cm³ gas at temperature T. (From data of ref. 8)

These results are important for bath-cooled superconducting coils relying on convection of liquid helium in narrow channels between the windings. If a disturbance requires the dissipation of a certain amount of heat above the threshold value – presumably determined by the geometry of the channels – the anomalous heat transport could lead to a premature quench. A remedy might be to set up sufficient convection before disturbances occur. On the other hand the effect could be useful for rapid quench propagation.

VI Discussion and conclusion

Two heat transfer effects were reported, both incidentally observed in an apparatus originally designed for steady state experiments. The study is but preliminary and far from complete. It was reported at this stage because it points to effects that might be of concern in coil designs using the traditional bath cooling. Of the two phenomena described, one, the SNZ effect, once sufficiently understood, could be clearly beneficial, while the other, heat transport by superheated bubbles, may be very troublesome.

The reported phenomena illustrate some of the complexities of heat transfer into helium and consequently indicate our insufficient understanding of a process that is crucial to the stability of operation in the superconducting current carrying state.

The SNZ has been used to measure localized heat transfer, especially in the temperature region between film boiling and nucleate boiling.

The anomalous heat transport indicates a time dependence of the heat transfer of the order of tenths of seconds and is likely to have a convective mechanism.

Both, localized and time dependent heat transfer are germane to instabilities in superconductors and to onset of quenching, whereas steady state heat transfer is not applicable.

Acknowledgements

The author thanks Steve Sydoriak, with whom he built the apparatus jointly, for the use of his laboratory and assistance during measurements. Thanks are also due to J. O. Willis for calibrating the thermometers.

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